

# Medial meniscus posterior root tear causes swelling of the medial meniscus and expansion of the extruded meniscus: a comparative analysis between 2D and 3D MRI

## Abstract

**Purpose:** This study aimed to clarify the advantages of three-dimensional (3D) magnetic resonance imaging (MRI) over two-dimensional (2D) MRI in measuring the size of the medial meniscus (MM), and to analyse the volumes of MM and the extruded meniscus in patients with MM posterior root tear (MMPRT), at 10° and 90° knee flexion.

**Methods:** This study included 17 patients with MMPRTs and 15 volunteers with uninjured knees. The MMs were manually segmented for 3D reconstruction; thereafter, the extruded part separated from the tibial edge was determined. The length, width, height, and extrusion of MM were measured by the 2D and 3D methods, and compared. The MM volume, extruded meniscus volume, and their ratio were also calculated using 3D analysis software in the two groups.

**Results:** The estimated length and posterior height of MM was larger with 3D MRI than with 2D MRI measurements. The MM volume was significantly greater in MMPRT knees than in normal knees, with increasing MM height. In MMPRT knees, the mean volume of the extruded meniscus and its ratio significantly increased by 304 mm<sup>3</sup> ( $p = 0.02$ ) and 9.1% ( $p < 0.01$ ), respectively, during knee flexion.

**Conclusions:** This study demonstrated that 3D MRI could estimate the precise MM size, and that MMPRT caused meniscus swelling due to the increased thickness in the posteromedial part. The

20 clinical significance of this study lies in its 3D evaluation of MM volume, which should help the  
21 surgeon understand the biomechanical failure of MM function and improve MMPRT repair technique.

22

### 23 **Level of Evidence: III**

24 **Keywords:** Medial meniscus; Posterior root tear; Osteoarthritis; Meniscal volume; Medial extrusion;  
25 Three-dimensional magnetic resonance imaging; Flexed-knee position.

26

### 27 **Abbreviations**

28	2D	Two-dimensional
29	3D	Three-dimensional
30	CI	Confidence interval
31	ICC	Intra-class correlation coefficient
32	Iso FSE	Isotropic resolution fast spin-echo
33	LM	Lateral meniscus
34	MM	Medial meniscus
35	MMBW	Medial meniscus body width
36	MMEV	Medial meniscus extrusion volume
37	MML	Medial meniscus length
38	MMME	Medial meniscus medial extrusion

39	MMPE	Medial meniscus posterior extrusion
40	MMPH	Medial meniscus posterior height
41	MMPRT	Medial meniscus posterior root tear
42	MMRV	Medial meniscus remaining volume
43	MMV	Medial meniscus volume
44	MPL	Medial plateau width
45	MRI	Magnetic resonance imaging
46	OA	Osteoarthritis
47	TPW	Total plateau width
48		

## 49 **Introduction**

50 Medial meniscus (MM) posterior root tear (MMPRT) is defined either as a complete radial tear that  
51 is located within 9 mm of the MM posterior insertion or as a bony avulsion of the root attachment  
52 [1,21]. MMPRT results in notable medial meniscus extrusion (MME) and gap formation at the root  
53 avulsion site when compressive loads are applied at the knee, representing functional failure of the  
54 load transmission into hoop strain [18,26,30]. Many studies reported that an MME of  $\geq 3$  mm on  
55 magnetic resonance imaging (MRI) was significantly associated with articular cartilage degeneration  
56 [20,33].

57 One of the main disadvantages of two-dimensional (2D) MRI measurements is that they rely on  
58 particular coronal and sagittal slices, which makes it difficult to precisely define the meniscus size,  
59 including its length, width, and height in its curved regions (i.e., body and anterior and posterior  
60 horns) [23,31,35]. Thus, a three-dimensional (3D) MRI-based technology has been developed to  
61 measure the meniscus size and its position relative to the tibia [2-4]. Recently, 3D MRI has been  
62 used to determine the meniscal volume and quantify the entire meniscus [9]. However, it is largely  
63 unclear whether the 3D method is superior to the 2D method.

64 Studies involving the measurement of meniscal volume have been conducted for knees with  
65 osteoarthritis (OA). Wirth et al. reported that the MM volume (MMV) was greater in OA than in  
66 non-OA knees [35], while cohort studies showed that MMVs did not differ between OA and non-OA  
67 knees [2,34], indicating the existence of variations in MMV. A recent analysis confirmed that the

68 volume of the extruded meniscus from the tibia was greater in OA knees than in non-OA knees [9].

69 However, to our knowledge, no study has compared the volumes of the entire MM and extruded MM

70 between MMPRT and normal knees in the knee-flexed position.

71 The purpose of this study was to clarify the benefit of 3D MRI by examining differences in MM

72 size between 2D and 3D measurements and to analyse the volumes of entire MM and extruded MM

73 in MMPRT and normal knees, at 10° and 90° of knee flexion. Our hypotheses were as follows: (1)

74 3D MRI would provide the precise length, width, and height of the meniscus; (2) entire MMV would

75 not differ between MMPRT knees and normal knees; and (3) MM extrusion volume (MMEV) would

76 be larger in MMPRT knees than in normal knees. This study involved a novel 3D method for

77 evaluating MMVs, which could provide clinical information that reveals altered joint biomechanics

78 in MMPRT knees.

79

## 80 **Materials and methods**

81 From August 2017 to September 2018, 32 knees in 32 subjects who underwent MRI examinations at

82 Okayama University Hospital were included. This retrospective study consisted of 17 female patients

83 with MMPRT and 15 female volunteers with normal (uninjured) knees. The MMPRT patients were

84 found to passively have characteristic MRI findings (ghost /cleft/radial tear signs of MM posterior

85 root from the attachment and the giraffe neck sign [7,12]) at the initial MRI, and were limited to

86 those who provided informed consent for additional 3D MRI examination. Of these, patients who

87 had radiographic knee OA with Kellgren-Lawrence grade III or higher and a previous history of  
88 meniscus injuries were excluded. Female nurses in our hospital were recruited in this study as  
89 volunteers, and were limited to middle-aged and elderly women to match the characteristics of the  
90 MMPRT patients. To compare the knee size in both groups, the total plateau width (TPW) and  
91 medial plateau length (MPL) were measured on MRI-based coronal and sagittal planes [23,31]. TPW  
92 was defined as the distance from the most medial to the lateral aspect of the tibia. MPL was  
93 measured as the distance of the maximal anteroposterior length of the medial plateau. The mean  
94 duration from MMPRT onset to MRI examination was 78 (range, 13-235) days. MMPRT types were  
95 identified by careful arthroscopic examinations according to the LaPrade classification as follows:  
96 type 1 and 2 tears were partial and complete radial tears, respectively, within 9 mm of the centre of  
97 the root attachment; type 3 tears were bucket-handle tears; type 4 tears were complex oblique  
98 meniscal tears extending into the root attachment; and type 5 tears were avulsion fractures of the  
99 meniscal root attachment [22].

100

#### 101 ***MRI protocol and 3D model preparation***

102 MRI was performed using the Oasis 1.2 Tesla (Hitachi Medical, Chiba, Japan), with a coil in the 10°  
103 and 90° knee-flexed positions in a non-weight-bearing condition (Fig. 1a, b; 2a, b). Knee flexion  
104 angle was measured using a knee goniometer, with the knee held in neutral rotation. Multiplanar  
105 images were acquired using proton density-weighted isotropic resolution fast spin-echo (iso FSE,

106 Hitachi Medical) sequence with continuous 1-mm slice thickness. The 3D FSE images were applied  
107 in the sagittal and coronal planes with repetition time/echo time, 600/96; matrix, 224×224; field of  
108 view, 18 cm; 1 average; echo-train length, 24; bandwidth, ±98.1 kHz; and scanning time, 4.8 min.

109 Data on the femur and tibia were extracted semi-automatically with the voxel density threshold for  
110 the surface definition using the 3D image analysis workstation SYNAPSE VINCENT® (Fuji Medical  
111 System, Tokyo, Japan). Segmentations of the meniscus using the texture tracing technique [17,29]  
112 were performed manually by a radiologic technologist (T.Y) and two orthopaedic surgeons (Y.O and  
113 T.F). After the segmentation process, three kinds of 3D reconstructed meniscus were obtained by the  
114 volume-rendering method [8,25] (Fig. 1c, d; 2c, d).

115

### 116 ***Comparative analysis between the 2D and 3D measurements***

117 The conventional 2D measurement was performed using a simple MRI-based meniscal sizing  
118 method [13, 24]. A posterior condylar line was drawn passing on the most posterior edge of the  
119 femoral condyles. The sagittal and coronal planes were created vertical and parallel to the posterior  
120 condylar line, respectively. The 2D parameters were measured in the sagittal plane where the medial  
121 meniscus length (MML) was longest (Fig. 1a, 2a), and in the coronal plane where the medial  
122 meniscus body width (MMBW) was widest (Fig. 1b, 2b) MML was defined as the length from the  
123 anterior to the posterior edge of MM. MMBW was measured from the outer to the inner border of  
124 MM. Medial meniscus posterior height (MMPH) was defined as the height from the lowest to the

125 highest point in the posterior segment of MM. Medial meniscus medial extrusion (MMME) was  
126 measured from the medial edge of the tibia to the outer border of MM in the coronal plane. Medial  
127 meniscus posterior extrusion (MMPE) was defined as the distance from the posterior edge of the  
128 tibia to the posterior border of MM in the sagittal plane.

129 The 3D-based measurement was conducted by applying a method similar to the sizing technique  
130 for meniscal allografts [23, 31]. A 3D model of the meniscus was observed from above the axial  
131 plane, which was taken parallel to the tibial plateau (Fig. 1c, 2c). First, a reference line was created  
132 intersecting the tibial intercondylar spines. The anterior and posterior borders of MM were  
133 determined parallel to the reference line. MML was the distance measured from the anterior to the  
134 posterior border of MM. MMBW was defined as the width from the outermost border to the  
135 innermost border of MM. The MME area was created by identifying the outline of the tibia plateau,  
136 and cutting the inner part of MM through the outline, as previously described [9] (Fig. 1d, 2d).  
137 MMME was measured as the distance from the medial edge of the tibia to the MM outer edge.  
138 MMPE was defined as the distance from the posterior edge of the tibia to the posterior border of  
139 MM. In addition, MMPH was defined as the height from the lowest to the highest point in the MM  
140 posterior segment on the coronal plane perpendicular to the tibial plateau. The average of the 3D  
141 measurements recorded by the three observers was calculated and compared with the average of the  
142 2D measurements.



143 To evaluate the repeatability of the above parameters, test-retest reliability calculations were  
144 conducted at time intervals of >10 weeks, using the intra-class correlation coefficient (ICC), with the  
145 95% confidence interval (CI).

146

#### 147 *Volume analysis of MM and the extruded meniscus*

148 Volume measurement of the meniscus was performed via voxel counting, which was calculated by  
149 the summation of all voxel volumes lying within the boundaries; this has been reported as a valid and  
150 accurate method of volume analysis [35]. All 3D images in the present study had a reconstructed  
151 matrix size of 512×512, pixel size of 0.352 mm<sup>2</sup>, and slice thickness of 1 mm. The volume of each  
152 voxel was 0.124 mm<sup>3</sup>, according to the following formula: 1×0.352×0.352. After visual confirmation  
153 of the exact segmentation of MM, the SYNAPSE VINCENT<sup>®</sup> software accomplished the MMV  
154 measurements automatically.

155 MMEV was defined as the volume of the extruded meniscus beyond the inner articular part of  
156 MM (Fig. 1d, 2d). The MMEV ratio was calculated as MMEV divided by MMV to adjust for  
157 individual differences. In addition, the negative MMV in the inner articular part was determined as  
158 the remaining MMV (MMRV). The MMRV ratio (MMRV / MMV×100) was also calculated.

159 The 3D parameters (MML, MMBW, MMPH, MMME, and MMPE) and these volume  
160 measurements were compared between MMPRT knees and normal knees at 10° and 90° of knee  
161 flexion.

162

163 ***Reliability evaluation of the 3D segmentation***

164 A radiologic technologist and two orthopaedic surgeons (Y.O and T.F) retrospectively segmented  
165 MM and defined the MME area manually. The technologist segmented MM and the MME area in a  
166 blinded manner, at 12 weeks after the first examinations, followed by automatic volume calculations.  
167 The inter- and intra-observer reliabilities of the MRI volume measurements were assessed using the  
168 ICC. An ICC of  $\geq 0.75$  was considered excellent,  $\geq 0.60$  to  $< 0.75$  good;  $\geq 0.40$  to  $< 0.60$  fair, and  $<$   
169  $0.40$  poor [32].

170

171 ***Validation study of meniscus volume***

172 Six intact lateral menisci (LMs) were obtained during total knee arthroplasty in patients (2 women  
173 and 4 men) with medial compartmental OA of the knee. The MRI scan of each LM was taken using  
174 the abovementioned 3D protocol. Manual segmentation via the SYNAPSE VINCENT® software was  
175 performed by the three observers and the calculation values averaged. Thereafter, the 3D MRI-based  
176 volume was compared to its water suspension volume [14]. The suspension method has been shown  
177 to be an accurate technique for volume measurement, using Archimedes' principle, which involves  
178 suspending an object (meniscus) in a water-filled container placed on electronic weight scales. Each  
179 water suspension volume measurement was repeated three times, and the values were averaged.

180 This study was approved by the Institutional Review Board of Okayama University Graduate  
181 School (ID number of the approval: 1857) and written informed consent was obtained from all  
182 subjects before the MRI examinations.

183

#### 184 ***Statistical analysis***

185 IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA) was used for all statistical analyses.  
186 The differences in 2D vs 3D MRI measurements were examined using paired *t*-tests. The Mann-  
187 Whitney *U*-test was used to compare the 3D MRI measurements between the two groups, and the  
188 changes from 10° to 90° knee flexion. Data are presented as mean ± standard deviation and significance  
189 was set at  $p < 0.05$ . The correlation of difference in the validation study was analysed using parametric  
190 (Pearson *r*) correlation coefficients. The sample size was estimated using a power of 80% and  $\alpha$  of  
191 0.05. The samples of MML and MMPH needed in the first comparative study was 15 in each group.  
192 The required sample size for MMPH and MMV in the second comparative study was 15 in each group.

193

#### 194 **Results**

##### 195 ***Characteristics of study participants***

196 The two groups did not differ significantly (n.s.) with regard to age, height, body weight, and body  
197 mass index (Table 1). There were also no significant differences in terms of knee sizes involving  
198 TPW and MPL. The MMPRT groups included 15 radial tears (type 2) and two oblique tears (type 4).

199

200 ***Comparative analysis between the 2D and 3D measurements***

201 *MMPRT knee*

202 At 10° of knee flexion, MML was significantly smaller in the 2D measurement than in the 3D  
203 measurement (mean difference;  $1.7 \pm 1.0$  mm,  $p < 0.001$ ) (Table 2). At 90° of knee flexion, MML  
204 and MMPH were significantly smaller in the 2D measurement than in the 3D measurement (mean  
205 difference;  $1.6 \pm 1.3$  mm,  $p < 0.001$  and  $1.4 \pm 1.0$  mm,  $p = 0.001$ ; respectively), while MMME and  
206 MMPE were greater in the 2D measurement than in the 3D measurement.

207 *Normal knee*

208 MML was significantly smaller in the 2D measurement than in the 3D measurement at 10° and 90°  
209 of knee flexion (mean difference;  $1.2 \pm 0.8$  mm,  $p = 0.011$  and  $1.8 \pm 1.3$  mm,  $p = 0.001$ ; respectively)  
210 (Table 2).

211

212 *Measurement repeatability*

213 The overall test-retest reliability data are shown in Table 3. Excellent repeatability was demonstrated  
214 in all 3D MRI measurements. Most ICCs were higher in 3D MRI measurements than in 2D MRI  
215 measurements.

216

217 ***Differences in the 3D measurements between MMPRT and normal knees***

218 *Flexion angle of 10°*

219 MMME, MMV, MMEV, and MMEV ratio were significantly greater in MMPRT knees than in  
220 normal knees, while the MMRV ratio was significantly lower in MMPRT knees (Table 4).

221 *Flexion angle of 90°*

222 MMPH, MMME, MMPE, MMV, MMEV, and MMEV ratio were significantly greater in MMPRT  
223 knees than in normal knees (Table 4). In contrast, MMRV and MMRV ratio were smaller in  
224 MMPRT knees than in normal knees.

225

226 **Volume changes from 10° to 90° knee flexion**

227 There was no significant difference in MMV between 10° and 90° knee flexion. MMEV and MMEV  
228 ratio in the MMPRT knee were significantly increased ( $p = 0.020$  and  $0.001$ , respectively) (Fig. 3),  
229 while MMRV ratio in the MMPRT knee was significantly decreased by 9.1% ( $p = 0.001$ ).

230 Figure 4 shows representative cases in both groups. At 10° knee flexion, MME areas were  
231 observed between the anterior and medial parts of the MM (Fig 4a, b). However, at 90° knee flexion,  
232 compared to the normal knee, the MM posterior root in the MMPRT knee was widely detached and  
233 the MME area was translocated to the posteromedial direction of MM (Fig 4c, d). In addition, the  
234 extruded MM in MMPRT knees was thickened.

235

236 ***Reliability evaluation of the 3D segmentation***

237 *Inter-observer reliability*

238 The ICC of MMV at 10° and 90° knee flexion was 0.89 (95% CI 0.75- 0.96) and 0.85 (95% CI 0.65-  
239 0.94), respectively. The ICC of MMEV at 10° and 90° knee flexion was 0.86 (95% CI 0.67-0.95) and  
240 0.84 (95% CI 0.63-0.94), respectively.

241 *Intra-observer reliability*

242 The ICC of MMV at 10° and 90° knee flexion was 0.96 (95% CI 0.90- 0.99) and 0.89 (95% CI 0.69-  
243 0.96), respectively. The ICC of MMEV at 10° and 90° knee flexion was 0.90 (95% CI 0.72-0.97) and  
244 0.89 (95% CI 0.68-0.96), respectively.

245

246 *Validation analysis of the meniscus volume*

247 The mean volume of the removed LM was  $3016 \pm 758 \text{ mm}^3$  in the water suspension measurements  
248 and  $2901 \pm 606 \text{ mm}^3$  in the 3D MRI measurements. An excellent correlation of coefficients was  
249 observed ( $r = 0.98$ ). The mean absolute error between the two volume measurements was 4.6%.

250

251 **Discussion**

252 This comparative analysis demonstrated that 2D MRI measurement underestimated MM size and  
253 that 3D MRI achieved a higher measurement accuracy than 2D MRI. A major benefit of 3D MRI  
254 could be its ability to estimate the precise size and shape of the entire meniscus as indicated by the  
255 excellent repeatability shown in this study. In addition, to our knowledge, this is the first study to

256 apply the SYNAPSE VINCENT<sup>®</sup> to the analysis of the meniscal volume. The present validation  
257 study showed an excellent correlation between the volume measurement in our study and that  
258 derived from Archimedes' principle. Moreover, the absolute error was low, and was superior to that  
259 in the study of Bowers et al (MM; 4.6%, LM; 7.9%) [5]. These results indicate that the Vincent  
260 method is accurate for estimating the meniscal volume.

261 Previous studies that directly compared 2D MRI with cadaveric meniscus sizing demonstrated  
262 various differences in measurements. Shaffer et al. showed that only 37% of the 2D MRI  
263 measurements were accurate to within 2 mm of the true meniscal dimensions [31]. Carpenter et al.  
264 also found that conventional MRI consistently underestimated MM length (mean error 2.6 mm) [6].  
265 Conversely, in this study, the 3D measurement with larger MML is suggestive of approaching the  
266 precise length of the MM. Interestingly, we also discovered that 2D MRI underestimated MMPH in  
267 the MMPRT knee, especially at 90° knee flexion. In fact, the meniscal deformation was visualised in  
268 the 3D reconstructed model (Fig. 4), which demonstrated that the extruded MM expanded to the  
269 posteromedial direction with increasing meniscus thickness. This implies that 2D MRI, which relied  
270 on coronal and sagittal images, could not accurately evaluate the meniscus height and extrusion in  
271 the posteromedial region.

272 One important finding is that MMV was larger in the MMPRT knee than in the normal knee; thus,  
273 contradicting the second hypothesis in the present study. The large MMV could have been due to the  
274 greater values of MML, MMBW, and MMPH in MMPRT (Table 4). A previous 3D study of OA

275 knees demonstrated that meniscal thickness and width were significantly greater in OA knees than in  
276 non-OA knees [35]. The reason for this is that medial compartmental OA increases the load on the  
277 MM, which is then displaced externally due to the loss of hoop tension and high biomechanical  
278 stress. Hence, MM is squeezed towards the unloaded outer joint, which may cause swelling [34]. It is  
279 conceivable that the same phenomenon occurred in the MMPRT knee with a disrupted hoop-strain  
280 mechanism. However, a histological analysis reported that a degenerative change in the posterior  
281 horn might precede complete MMPRT [28]. This analysis also showed that the collagen architecture  
282 was disorganised with the extent of the tear and the widening of the root was observed in partial and  
283 complete tears. Therefore, a potential explanation is that MM swelling may exist before the  
284 occurrence of MMPRT.

285 An MRI analysis showed that during knee extension to deep flexion, the posterior translation of  
286 normal MM ( $3.3 \pm 1.5$  mm) was less than that of LM due to the strong attachment on the MM  
287 posterior root [36]. Recent open MRI studies have also shown that the MM posterior horn had a  
288 buttress effect and a more convex shape by compression force on the posterior condyle at 90° knee  
289 flexion [15,24]. In contrast, the present study showed that MMPE in the MMPRT knee increased by  
290 6.3 mm (or 6.5 mm) from 10° to 90° knee flexion, and that MMEV and MMEV ratio were greater  
291 than in the normal knee. Thus, we believe that the posterior femoral condyle compresses the torn  
292 MM in the posteromedial direction and the unloaded MM margin becomes thicker. Of note, this



293 study showed the reduction of MMRV in the MMPRT knee, suggesting the loss of MM function as a  
294 load transmitter [26,27,30].

295 There were several limitations to the present study. First, only a few subjects could be evaluated  
296 because of the discomfort involved in keeping the knee flexed for about 50 minutes during MRI.  
297 Second, the 3D MRI measurement could not be compared with the true meniscus size, such as  
298 obtained using cadaveric knees. Further studies are needed to verify the accuracy of 3D meniscal  
299 sizing. Third, the MMV measurements were conducted without joint loading; hence, the magnitude  
300 of MMEV might have been underestimated. To assess the mechanical change in MMV under load  
301 conditions will be necessary. Finally, the inter- and intra-reliability using the Vincent method were  
302 relatively lower than in a previous cadaveric study (ICC = 0.96) [5]. This lower reliability can be  
303 attributed to the difficulty in identifying the meniscal borders with little anatomical separations,  
304 especially in MMPRT with large MME. Observers should standardise the meniscus outer border,  
305 such as the meniscosynovial rim [16], in addition to adjusting the MRI intensity to low-signal intra-  
306 meniscus and high-signal extra-meniscus. Despite these limitations, open 3D MRI-based  
307 reconstruction can provide accurate meniscus volume and visualisation of meniscal translation with  
308 the MM bulging.

309 This study is clinically relevant in that 3D MRI can be used to clarify the mechanism of the  
310 swelling and posteromedial extrusion of MM in MMPRT knees. This 3D method using SYNAPSE

311 VINCENT<sup>®</sup> could help surgeons to improve surgical techniques including pull-out repairs [10,11,  
312 19] and to evaluate the surgical outcome via postoperative MMV and MMEV changes.

313

## 314 **Conclusions**

315 This comparative analysis demonstrated that the estimated maximum length and posterior height of  
316 MM was greater with 3D MRI than with 2D MRI measurements, indicating that 3D MRI can  
317 precisely evaluate the meniscal size including its dimension and volume. This study also revealed the  
318 enlargement of MMV and MMEV in MMPRT knees, which is attributed to a biomechanical failure  
319 of load transmission and degenerative change in the meniscus.

320

## 321 **Acknowledgement**

322 This study was supported by Takatsugu Yamauchi and Hiroki Ichikawa, who are radiologic  
323 technologists, and who took accurate MRI measurements and reviewed the 3D MRI protocol. We are  
324 grateful to Dr. Shinichi Miyazawa for the validation analysis.

325

## 326 **Funding**

327 No funding was received.

328

## 329 **Compliance with ethical standards**

330    **Conflict of interest**

331    The authors report no conflicts of interest.

332

333    **Ethical approval:** All procedures performed in studies involving human participants were in  
334    accordance with the ethical standards of the institutional review board.

335

336

## REFERENCES

1. Allaire R, Muriuki M, Gilbertson L, Harner CD (2008) Biomechanical consequences of a tear of the posterior root of the medial meniscus. Similar to total meniscectomy. *J Bone Joint Surg Am* 90:1922–1931
2. Bloecker K, Guermazi A, Wirth W, Benichou O, Kwok CK, Hunter DJ, Englund M, Resch H, Eckstein F, OAI investigators (2013) Tibial coverage, meniscus position, size and damage in knees discordant for joint space narrowing e data from the Osteoarthritis Initiative. *Osteoarthritis Cartilage* 21: 419e27.
3. Bloecker K, Wirth W, Guermazi A, Hitzl W, Hunter DJ, Eckstein F (2015) Longitudinal change in quantitative meniscus measurements in knee osteoarthritis-data from the Osteoarthritis Initiative. *Eur Radiol* 25:2960–2968
4. Bloecker K, Wirth W, Hudelmaier M, Burgkart R, Frobell R, Eckstein F (2012) Morphometric differences between the medial and lateral meniscus in healthy men - a three-dimensional analysis using magnetic resonance imaging. *Cells Tissues Organs* 195:353–364
5. Bowers ME, Tung GA, Fleming BC, Crisco JJ, Rey J (2007) Quantification of meniscal volume by segmentation of 3T magnetic resonance images. *J Biomech* 40:2811–2815
6. Carpenter JE, Wojtys EM, Houston LJ (1993) Preoperative sizing of meniscal allografts. *Arthroscopy* 9:344
7. Choi SH, Bae S, Ji SK, Chang MJ (2012) The MRI findings of meniscal root tear of the medial

- meniscus: emphasis on coronal, sagittal and axial images. *Knee Surg Sports Traumatol Arthrosc* 20:2098–2103
8. Doumouchtsis SK, Nazarian DA, Gauthaman N, Durnea CM, Munneke G (2017) Three-dimensional volume rendering of pelvic models and paraurethral masses based on MRI cross-sectional images. *Int Urogynecol J* 28:1579–1587
9. Dube B, Bowes MA, Kingsbury SR, Hensor EMA, Muzumdar S, Conaghan PG (2018) Where does meniscal damage progress most rapidly? An analysis using three-dimensional shape models on data from the Osteoarthritis Initiative. *Osteoarthritis Cartilage* 26:62–71
10. Fujii M, Furumatsu T, Kodama Y, Miyazawa S, Hino T, Kamatsuki Y, Yamada K, Ozaki T (2017) A novel suture technique using the FasT-fix combined with Ultrabraid for pullout repair of the medial meniscus posterior root tear. *Eur J Orthop Surg Traumatol* 27: 559–562
11. Furumatsu T, Kodama Y, Fujii M, Tanaka T, Hino T, Kamatsuki Y, Yamada K, Miyazawa S, Ozaki T (2017) A new aiming guide can create the tibial tunnel at favorable position in transtibial pullout repair for the medial meniscus posterior root tear. *Orthop Traumatol Surg Res* 103:367–371
12. Furumatsu T, Fujii M, Kodama Y, Ozaki T (2017) A giraffe neck sign of the medial meniscus: a characteristic finding of the medial meniscus posterior root tear on magnetic resonance imaging. *J Orthop Sci* 22:731–736
13. Furumatsu T, Miyazawa S, Tanaka T, Okada Y, Fujii M, Ozaki T (2014) Postoperative change

- 375 in medial meniscal length in concurrent all-inside meniscus repair with anterior cruciate ligament  
376 reconstruction. *Int Orthop* 38:1393–1399
- 377 14. Hughes FW (2005) Archimedes revisited: a faster, better, cheaper method of accurately  
378 measuring the volume of small objects. *Physics Education* 40: 468–474.
- 379 15. Inoue H, Furumatsu T, Miyazawa S, Fujii M, Kodama Y, Ozaki T (2018) Improvement in the  
380 medial meniscus posterior shift following anterior cruciate ligament reconstruction. *Knee Surg  
381 Sports Traumatol Arthrosc* 26:434–441
- 382 16. Jones LD, Mellon SJ, Kruger N, Monk AP, Price AJ, Beard DJ (2018) Medial meniscal extrusion:  
383 a validation study comparing different methods of assessment. *Knee Surg Sports Traumatol  
384 Arthrosc* 26:1152–1157
- 385 17. Khan U, Yasin A, Abid M, Shafi I, Khan SA (2018) A methodological review of 3D  
386 reconstruction techniques in tomographic imaging. *J Med Syst* 42:190
- 387 18. Kim JG, Lee YS, Bae TS, Ha JK, Lee DH, Kim YJ, Ra HJ (2013) Tibiofemoral contact mechanics  
388 following posterior root of medial meniscus tear, repair, meniscectomy, and allograft  
389 transplantation. *Knee Surg Sports Traumatol Arthrosc* 21:2121–2125.
- 390 19. Kodama Y, Furumatsu T, Fujii M, Tanaka T, Miyazawa S, Ozaki T (2016) Pullout repair of a  
391 medial meniscus posterior root tear using a FasT-fix all-inside suture technique. *Orthop Traumatol  
392 Surg Res* 102:951–954
- 393 20. Kwak YH, Lee S, Lee MC, Han HS (2018) Large meniscus extrusion ratio is a poor prognostic

- 394 factor of conservative treatment for medial meniscus posterior root tear. *Knee Surg Sports*  
395 *Traumatol Arthrosc* 26:781–786
- 396 21. LaPrade CM, Ellman MB, Rasmussen MT, James EW, Wijdicks CA, Engebretsen L, LaPrade RF  
397 (2014) Anatomy of the anterior root attachments of the medial and lateral menisci: a quantitative  
398 analysis. *Am J Sports Med* 42:2386–2392
- 399 22. LaPrade CM, James EW, Cram TR, Feagin JA, Engebretsen L, LaPrade RF (2015) Meniscal root  
400 tears: a classification system based on tear morphology. *Am J Sports Med* 43:363–369
- 401 23. McDermott ID, Sharifi F, Bull AM, Gupte CM, Thomas RW, Amis AA (2004) An anatomical  
402 study of meniscal allograft sizing. *Knee Surg Sports Traumatol Arthrosc* 12:130–135.
- 403 24. Okazaki Y, Furumatsu T, Miyazawa S, Kodama Y, Kamatsuki Y, Hino T, Masuda S, Ozaki T  
404 (2019) Meniscal repair concurrent with anterior cruciate ligament reconstruction restores  
405 posterior shift of the medial meniscus in the knee-flexed position. *Knee Surg Sports Traumatol*  
406 *Arthrosc* 27:361–368
- 407 25. Otsubo H, Akatsuka Y, Takashima H, Suzuki T, Suzuki D, Kamiya T, Ikeda Y, Matsumura T,  
408 Yamashita T, Shino K (2016) MRI depiction and 3D visualization of three anterior cruciate  
409 ligament bundles. *Clin Anat* 30:276–283
- 410 26. Ozkoc G, Circi E, Gonc U, Irgit K, Pourbagher A, Tandogan RN (2008) Radial tears in the root  
411 of the posterior horn of the medial meniscus. *Knee Surg Sports Traumatol Arthrosc.*  
412 2008;16:849–854.

- 413 27. Padalecki JR, Jansson KS, Smith SD, Dornan GJ, Pierce CM, Wijdicks CA, Laprade RF (2014)  
414 Biomechanical consequences of a complete radial tear adjacent to the medial meniscus posterior  
415 root attachment site: in situ pull-out repair restores derangement of joint mechanics. *Am J Sports*  
416 *Med* 42:699–707
- 417 28. Park do Y, Min BH, Choi BH, Kim YJ, Kim M, Suh-Kim H, Kim JH (2015) The degeneration  
418 of meniscus roots is accompanied by fibrocartilage formation, which may precede meniscus root  
419 tears in osteoarthritic knees. *Am J Sports Med* 43:3034e44.
- 420 29. Roth M, Emmanuel K, Wirth W, Kwok CK, Hunter DJ, Eckstein F (2018) Sensitivity to change  
421 and association of three-dimensional meniscal measures with radiographic joint space width loss  
422 in rapid clinical progression of knee osteoarthritis. *Eur Radiol* 28:1844–1853
- 423 30. Seitz AM, Lubomierski A, Friemert B, Ignatius A, Durselen L (2012) Effect of partial  
424 meniscectomy at the medial posterior horn on tibiofemoral contact mechanics and meniscal hoop  
425 strains in human knees. *J Orthop Res* 30:934–942
- 426 31. Shaffer B, Kennedy S, Klimkiewicz J, Yao L (2000) Preoperative sizing of meniscal allografts in  
427 meniscus transplantation. *Am J Sports Med* 28:524–533
- 428 32. Shrout PE, Fleiss JL (1979) Intraclass correlations: uses in assessing rater reliability. *Psychol Bull*  
429 86:420–428
- 430 33. Svensson F, Felson DT, Zhang F, Guermazi A, Roemar FW, Niu J, Aliabadi P, Neogi T, Englund  
431 M (2019) Meniscal body extrusion and cartilage coverage in middle-aged and elderly without



- 432 radiographic knee osteoarthritis. *Eur Radiol* 29:1848–1854
- 433 34. Wenger A, Wirth W, Hudelmaier M, Noebauer-Huhmann I, Trattnig S, Bloecker K et al (2013)
- 434 Meniscus body position, size, and shape in persons with and persons without radiographic knee
- 435 osteoarthritis: quantitative analyses of knee magnetic resonance images from the osteoarthritis
- 436 initiative. *Arthritis Rheum* 65:1804e11.
- 437 35. Wirth W, Frobell RB, Souza RB, Li X, Wyman BT, Le Graverand MP, Link TM, Majumdar S,
- 438 Eckstein F (2010) A three-dimensional quantitative method to measure meniscus shape, position,
- 439 and signal intensity using MR images: a pilot study and preliminary results in knee osteoarthritis.
- 440 *Magn Reson Med* 63:1162–1171
- 441 36. Yao J, Lancianese SL, Hovinga KR, Lee J, Lerner AL (2008) Magnetic resonance image analysis
- 442 of meniscal translation and tibio-menisco-femoral contact in deep knee flexion. *J Orthop Res*
- 443 26:673–684

444 **Figure legends**

445 **Fig. 1** 2D and 3D segmentations using proton density-weighted iso FSE image, at 10°

446 **a.** The 2D sagittal plane with the longest MML (double-headed arrow), MMPH (vertical double-  
447 headed arrow), and MMPE (arrow). The anterior and posterior margins of MM (dotted lines), the  
448 highest and lowest borders of MM (solid lines), and posterior edge of the tibia plateau (dashed line).  
449 **b.** The 2D coronal plane with the greatest MMBW (double-headed arrow) and MMME (arrow). The  
450 inner and outer margins of MM (dotted lines), the outer edge of the tibia (dashed line). **c.** The 3D  
451 model of the whole meniscus covering the tibial plateau (cyan area) and extrusion area (purple area).  
452 A reference line (red dotted line) was drawn passing through the tibial intercondylar spines. MML  
453 (perpendicular double-headed grey arrow) and MMBW (double-headed grey arrow). **d.** The  
454 extrusion area (purple area) was defined as the region separated by the black dashed line, which  
455 represents the circumference points of the medial tibia. MMME (grey arrow) was the distance from  
456 the most medial edge of the tibia (dashed grey line) to MM (dotted grey line). MMPE (grey arrow)  
457 was the distance from the most posterior edge of the tibia (dashed grey line) and MM (dotted grey  
458 line)

459 **Fig. 2** 2D and 3D segmentations using proton density-weighted iso FSE image, at 90°

460 **a.** The 2D sagittal plane with the longest MML (double-headed arrow), MMPH (vertical double-  
461 headed arrow), and MMPE (arrow). **b.** The 2D coronal plane with the greatest MMBW (double-headed  
462 arrow) and MMME (arrow). **c.** The 3D model of the whole meniscus (cyan and purple areas) and tibial

463 plateau. A reference line (red dotted line) along the tibial intercondylar spines. MML (perpendicular  
464 double-headed grey arrow) and MMBW (double-headed grey arrow). **d.** The extruded area from the  
465 tibial posterior edge (purple area). MMME (grey arrow) and MMPE (perpendicular grey arrow)  
466

467 **Fig. 3** The changes in 3D MRI-based volume measurements in each group, from 10° to 90° knee  
468 flexion

469 **a.** MMV. **b.** MMEV. **c.** MMEV ratio ( $100 \times \text{MMEV}/\text{MMV}$ ).  $*p < 0.05$

470

471 **Fig. 4** Two cases involving a 60-year-old female patient with MMPRT (a, c) and a 59-year-old  
472 healthy woman with a normal knee (b, d). The purple area represents the MME area and the cyan  
473 area shows the inner part of the whole meniscus. The inlets below show the posterior part of the  
474 meniscus and MMPH measurements (double arrows), on the coronal reconstructed image

475 **a.** The MME area in the MMPRT case located along the medial part of the medial tibial plateau at  
476 10° knee flexion. **b.** The extrusion of normal MM was not widely recognised. **c.** The MM posterior  
477 root in the MMPRT case was separated from the posterior attachment. The MME area spread to the  
478 posteromedial direction with increasing MMPH. **d.** The normal MM was stabilised and MME  
479 partially lay on the posteromedial area